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Note on the Project's Organization

The investigation of asthenosphere dynamics was composed of two independent but coordinated research projects supported by NASA grants to Brown University (E. M. Parmentier, principal investigator) and Columbia University (W. F. Haxby, principal investigator). This is the final technical report for the work conducted at Lamont-Doherty Geological Observatory of Columbia University.

Background and Overview

The goal of the project was to investigate the nature of small-scale convection beneath the oceanic lithosphere. This investigation was prompted by the observation of lineated gravity anomalies in the Seasat altimeter-derived gravity field over the central Pacific Ocean (Haxby and Weissel, 1986). These anomalies were interpreted as evidence for small-scale convective rolls in the sub-oceanic asthenosphere resulting from the boundary layer instability associated with the thickening lithosphere (Buck and Parmentier, 1986). Our investigation focused on oceanic fracture zones, where sharp changes in boundary layer thickness, associated with the crustal age discontinuity, could be expected to accentuate and localize convective instabilities. E. M. Parmentier of Brown University conducted theoretical modelling experiments on the development of convection at oceanic fracture zones, including in his models the effects of compositional stratification and variable viscosity. I (Haxby), and a graduate student (P. Wessel), examined the altimetric geoid in the vicinity of major fracture zones in the Pacific for evidence of small-scale convection. The results of this examination were mixed. We did not find any clear evidence for asthenosphere dynamics. However, our analysis resulted in a clearer understanding of the nature of lithospheric deformation at large offset fracture zones, as described in Wessel, P. and W.F. Haxby, Thermal stresses, differential subsidence, and flexure at oceanic fracture zones, *J. Geophys. Res. 95,* 375-391, 1990 (included with this report).

Small-Scale Convection at Fracture Zones

Parmentier's 2-dimensional modelling studies of convection at fracture zones predict very large geoid anomalies. Temperature-viscosity models for the mantle which have been used to support the small-scale convection interpretation for lineated gravity anomalies, observed in the central Pacific, predict the rapid development of a boundary layer instability at fracture zones. The predicted expression of this instability in the geoid is a several meter geoid low roughly centered on the fracture zone. Including compositional stratification inhibits the instability somewhat, but merely delays the develpoment of pronounced deformation by a few million years.

The pronounced geoid effects predicted by the 2-dimensional convection models are not observed at any fracture zones. This may indicate either that the temperature-viscosity-composition models employed in the analysis are wrong (requiring a new explanation for the lineated gravity anomalies), or, more likely, that the 2-dimensional assumption in the model yields misleading results. Our approach to the problem was to examine geoid anomalies at fracture zones in detail, developing models to account for the geoid component associated with lithospheric deformation, and then to examine the residual geoid anomalies for any indication of asthenosphere dynamics. The lithospheric modelling study is described in the attached reprint and is summarized in the following section. The examination of residual geoid anomalies did not reveal any systematic pattern of short to intermediate wavelength (200-500 km) geoid anomalies such as might be indicative of asthenosphere dynamics.

Lithospheric Deformation at Fracture Zones

We developed a model for lithospheric flexure at fracture zones that included the effects of differential thermal subsidence (Sandwell, 1984) and differential thermal bending moments (Parmentier and Haxby, 1986) on a lithospheric plate with flexural rigidity that varies both in space and time. We then compared the model predictions with Geosat altimeter profiles crossing major fracture zones in the Pacific. The details of the model and analysis are described fully in Wessel and Haxby (1990, included in this report). The principal results of the lithospheric modelling study were that the characteristics of fracture zone geoid anomalies are well explained by a model in which the fracture zone remains a free boundary for 2-4 m.y. along the inactive part of the fracture zone. During this 2-4 m.y., the differential thermal subsidence is accomodated by slip at the fracture zone rather than by plate flexure. Also, the plate's response to thermal bending moments is accentuated; the young side of the fracture zone sustains significant thermal flexure because of the free boundary, resulting in a more prominent fracture zone trough. Another result of the modelling study is that the plate appears to be significantly thicker than results of modelling lithospheric deformation at seamounts (Watts *et al.*, 1980) have indicated. Our best results are for a plate thickness determined by the depth to the 600-700° C isotherm, in contrast to 400-500° C from studies of seamount flexure.

Principal Findings

1. We did not find any indication of asthenosphere dynamics in geoid anomalies at fracture zones. This negative result underscores the need to develop more general models for examining the 3-dimensional pattern of convection beneath oceanic plates. Also, even though our analysis of fracture zones yielded new insights as to the nature of lithospheric deformation, we are still a long way from understanding lithospheric mechanics to the point where subtle, short wavelength components of the geoid associated with astheonsphere dynamics can be reliably extracted.

2. We developed a model for lithospheric structure at fracture zones which explains the general characteristics of fracture zone geoid anomalies remarkably well. The model results indicate that fracture zones remain a free boundary for 2-4 m.y. along the inactive part of the fracture zone, and that the elastic plate thickness is determined by the depth to the 600-700° C isotherm.

Publications

Wessel, P. and W.F. Haxby, Thermal stresses, differential subsidence, and flexure at oceanic fracture zones, *J. Geophys. Res. 95,* 375-391, 1990

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NBTIF

1. A "database" composed of global MHD simulations of the magnetosphere is being installed in the CDHF data base. Several production runs for selected upstream solar wind conditions were performed and are being examined for inclusion in the data base.
2. The interactive data visualization tools that will be used by the project in conjunction with the simulation data are essentially ready. They were demonstrated at the November ISTP SWG, and various responses were elicited from the ISTP community. The AVS by Stardent Computer has been the basis of the tools. The software developed displays in three dimensions, the results of the global MHD model, interpolate these results onto the orbits of various spacecrafts, and overlays the resulting "time" series onto the actual spacecraft data. Demonstrations using ISEE 1 and 2 data have been set up for the simulation conference in Japan in April 1991 and the Spring 1991 AGU meeting.
3. A set of hybrid simulations of rotational discontinuities with the magnetic field rotating out of the coplanarity plane have been performed. It was found that for small angles between the magnetic field and the normal the behavior is similar to the one we found previously for the coplanar case. However for large angles (in excess of 60°) some RDs appear remarkably stable and do not relax to a state with a smaller field rotation. The relevance of the results to ISTP measurements in the magnetopause is being analyzed.

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4. The effects of rapid thinning of the magnetotail plasma sheet are being studied using the 2–D hybrid code. Various rates of the magnetic influx through the tail sheet boundary have been examined. A main reason for the study is to determine the wave signatures produced in the center of the tail as a function of the time length of the expansion phase of the substorm. Requirements for the Geotail measurements are being derived.
5. The stability of ion distributions required to maintain dynamic equilibrium in magnetospheric boundary layers have been examined for scale lengths comparable to the ion gyroradius. Heat flux instabilities appear to dominate the behavior of relatively broad discontinuities. Transport models for incorporation into the global models are being produced.
6. The solar wind-magnetosphere system comprises a variety of physical processes with a wide range of space and time scales. Recognizing its nonlinear, dissipative and non-equilibrium nature, the techniques developed recently in the study of nonlinear dynamical systems have been used to study the intrinsic properties of the magnetospheric activity such as substorms. The key feature of this study is the direct use of observational data such as the AE and AL indices. The time series data has been used to reconstruct the phase space of magnetospheric activity using the time delay and correlation sum techniques. The study so far have been carried out in three states. In the first stage the correlation dimension of magnetospheric activity was studied. This yielded a

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fractional dimension of 3.5 showing the fractal structure of magnetospheric activity and indicating its chaotic behavior. In the second stage the largest Lyapunov exponent, which characterizes the divergence of neighboring trajectories, was found to be positive with its inverse of ~ 15 min, showing that the system is indeed chaotic and consequently may be modeled by a few variables. Further the time scale over which the system becomes chaotic is a few times the characteristic time and thus agrees well with the earlier results obtained from techniques such as the linear prediction filter analysis. In the third state the singular system analysis was used to determine the actual number of degrees of freedom of the system. From the AE index this number was found to be 5 and this sets the stage for the construction of the dynamical equations that describe the magnetospheric activity. Currently the construction of the dynamical equations is in progress and is carried out by considering nonlinear couplings of up to the third order and using the least squares fit to compute the coefficients. The predictability of the equations will be analyzed by comparing the actual data with that generated by the model and this will define the predictability of the model.

7. The phase and group speed throughout the waveforms of low frequency ($\lesssim$ ion cyclotron frequency) packets in a two-fluid plasma are examined where local field gradients and nonlinear effects are substantial. The waveforms of the packets studied here vary spatially by a great an amount that no asymptotic

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wave theory can be usefully employed to estimate these speeds. Results from numerical simulations of the 1–D two-fluid equations are presented to show how the speeds are influenced by the local fluid parameters. From the spatial and time variation of the wave's magnetic field, a local wave number and wave frequency can be found which then yield phase speeds throughout the waveform. An exact expression for the phase speed is derived from the two-fluid equations. Nonlinear group speeds are estimated from the local energy flux and from the slopes of lines of constant wave number. Results from packets of either right or left helicity which propagate either parallel or oblique to a uniform magnetic field with amplitudes as strong as the local mean field are given. The effects of nonlinear dispersion in each case are revealed through a comparison with the evolution of a very small amplitude packet where only linear dispersion occurs. In cases where strong nonlinear steepening (wave collapse) occurs wave power spectra are also presented to show the efficiency in the generating new wave modes. This work is of importance for waves in the solar wind and, in particular, for rotational discontinuities in the solar wind where nonlinear dispersion is a primary evolutionary process.

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